PREDICTING BONE STRENGTH FROM DENTAL CONE BEAM COMPUTED TOMOGRAPHY

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ABSTRACT

Bone strength prediction is important for assessing fracture risk in patients with osteoporosis and in maintaining stabilization at the initial stages when patients receive orthopedic or dental implants into bone. Traditionally, orthopedic physicians use areal bone mineral density (BMD) measured using dual-energy X-ray absorptiometry (DXA) as an indicator for assessing bone strength. However, two-dimensional areal BMD does not reveal the geometric parameter characteristics of bones. Over the last 20 years, clinical orthopedics has often used peripheral quantitative computed tomography (pQCT) for densitometric parameters [volumetric cortical BMD (vCtBMD)] and geometric parameters (cross-sectional moment of inertia (CSMI)], and their derived bone strength index (BSI) as an indicator for assessing bone strength. Previous studies had demonstrated that pQCT is better than DXA in predicting bone strength. In the last 10 years, dental cone-beam computed tomography (CBCT) has become increasingly popular for evaluating alveolar bone quality and quantity before performing dental implants. However, no studies have examined the capability of CBCT in predicting bone strength. The purpose of this study was to compare the capabilities of CBCT for predicting cortical bone strength of the femurs and tibias of rats. We collected femurs and tibias from 10 rats to use as specimens, the bones were scanned using dental CBCT to measure the vCtBMD and the CSMI for calculating the BSI. A three-point bending test was then conducted to measure the fracture load of each femur and tibia. Bivariate linear Pearson analysis was used to calculate the correlation coefficients (r) between the CBCT measurements and the three-point bending parameters. From the experimental results, the correlation between fracture load and the vCtBMD (measured using CBCT) for the femur and tibia were 0.63 and 0.78, respectively. The correlation between fracture load and the CSMI (measured using CBCT) for the femur and tibia were 0.77 and 0.78, respectively. For the correlation between BSI and fracture load, the correlation coefficient was 0.82 and 0.86 for femurs and tibias, respectively. CBCT is a useful tool to predict cortical bone fracture loads in rat femurs and tibias. The adoption of BSI, which is a combined index of densitometric and geometric parameters, was especially useful.

Keywords *Cone-beam computed tomography (CBCT); three-point bending; Bone strength; Rat femur; Rat tibia*

1. INTRODUCTION

Measuring bone strength using non-invasive methods is important for evaluating fracture risk according to the severity of osteoporosis, as well as to the early-stage stabilization of artificial implants after implantation in bone. Dual-energy X-ray absorptiometry (DXA) is one of the methods commonly used in the clinical field of orthopedics for evaluating bone mineral content (BMC) and bone mineral density (BMD) [1-3]. However, the areal BMD (g/cm^2) measured through DXA is calculated by dividing the obtained BMC(g) by the projected bone area (cm^2). Bone quality should not and cannot be identified simply using BMD. In addition to the intrinsic mechanical quality of bones, their geometric characteristics are important attributes for bone strength. However, BMD obtained using DXA is two-dimensional bone density information that does not provide data regarding the structural stiffness characteristics of the bone's shape.

In recent years, in addition to quantitative computed tomography (QCT) and peripheral quantitative computed tomography (pQCT) which are commonly used in orthopedics, the dental field has developed dental computed tomography, also known as dental cone beam computed tomography (CBCT). The resolution of CBCT (approximately 75-400 μm) is better than that of traditional CT. Nomura et al. found [4] a high correlation between CBCT and BMD, and some researchers have used CBCT to examine patients' alveolar bone density to serve as references of pre-surgical evaluation for dental implants [5,6]. Furthermore, the dosage required for CBCT is much less than that for traditional CT [7,8]. Although several studies have evaluated the feasibility of pQCT and DXA for measuring bone strength, few have examined the ability of dental CBCT to assess cortical bone strength. Most studies have focused on CBCT as a tool for evaluating alveolar bone density before performing dental implants. Therefore, the purpose of this study is to compare the ability of CBCT to predict cortical bone strength in rat femurs and tibias.

2. MATERIALS AND METHODS

2.1 Specimen preparation

10 femurs and 10 tibias were collected from 5 healthy male Sprague-Dawley rats (4 months of age, weight = 328 ± 4g). The femurs and tibias of each rat were harvested within 5 min after sacrifice. The bone specimens were wrapped with gauze soaked in saline and stored in a -20˚C freezer.

2.2 Dental CBCT measurements

A Dental CBCT (AZ 3000, Asahi Roentgen Ind. Co., Japan) was used to obtain the CBCT images of each femur and tibia (Figure 1). The scanning parameters were set at 85kV, 4 mA, and a voxel resolution of 155 μm. When performing the CBCT scans for all bone specimens, 2 phantoms with a pre-determined HA concentration [0.25 and a 0.75 g/cm^3 HA BMD phantom obtained from Skyscan (Skyscan, Aartselaar, Belgium)] were established and placed to calculate the vCtBMD of the bones. Thereafter, the CBCT images were loaded into professional medical imaging software (Mimics, Materialise, Leuven, Belgium) to calculate the vCtBMD (g/cm^3) of the midshaft portion of the femurs and tibias (Figure 2). 5 images of the midshaft portion of each femur and tibia were then imported into an ImageJ 1.45s (Rasband, W.S., ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA) to measure the CSMI (mm^4) of the femurs and tibias and finally calculating the BSI, which was calculated as vCtBMD × CSMI.

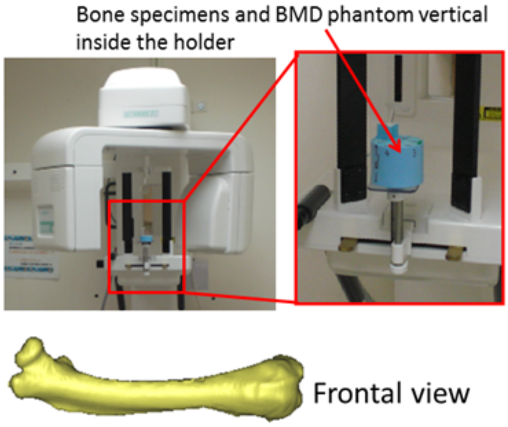

Figure 1. The CBCT machined used in this study and the 3D model of rat femur #3.

2.3 Three-point bending test

Each of the femurs and tibias had their soft tissues removed and were placed on a specially-designed loading apparatus on the material testing system (JSV-H1000, Japan Instrumentation System, Nara, Japan), as shown in Figure 2. The loading points on the femurs and tibias were at distances that were 40% and 45% of the total femoral and tibial lengths from the anatomic inferior side. The 2 supporting locations were located at a distance of 20 mm (Figure 2). A static preload of 1 N was applied to fix the bone specimens between the contacts. The loading speed of the crosshead was set to 20 mm/min using the displacement control mode. The force-displacement data were acquired and recorded at a sampling rate of 40 points/second until the bone specimen was fractured. The strength (fracture load) was determined as the highest point of the curve.

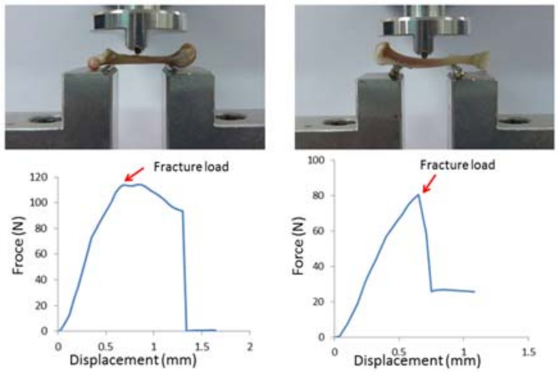

Figure 2. 5 The three-point bending test: (Left) femur (Right) tibia. (These images are of the force-displacement curve recorded from the three-point bending experiment for femur #6 and tibia #10.)

2.4 Statistical analysis

Mann-Whitney U test was used to compare the differences in the measurements and testing results of the CBCT and the three-point bending test between the femurs and tibias. A bivariate linear Pearson analysis was used to calculate the correlation coefficients (r) between the CBCT measurements and the three-point bending parameters. All statistical analyses of the data were performed using OriginPro software (Version 8, OriginLab, Northampton, MA, USA.). The level of the statistical significance was set at $P<0.01$.

2.4 Statistical Analysis

Descriptive statistics were computed to classify the probability distribution as either using the Cartesian coordinate system or the cylindrical coordinate system. All data were statistically analyzed using OriginPro software (Version 8, OriginLab, Northampton, MA, U.S.A.).

3. RESULTS

3.1 Densitometric, geometric, and mechanical test results

A summary of the measured denositometric, geometric, and mechanical parameters of the rat femurs and tibias are shown in Table 1. The coefficient of variation (CV) of the BSI was the largest parameter: 32.75% and 34.60% for femurs and tibias, respectively. The fracture load had the smallest CV: 6.20% and 8.81% for femurs and tibia, respectively. The parameters associated with densitometric parameter (vCtBMD), the geometric characteristics (CSMI), combined the densitometric parameters and geometric characteristics (BSI, calculated as CSMI × vCtBMD), and the fracture load of the femurs were significantly higher than those of the tibias (P<0.001).

Table 1. The experimental measurements of denositometric and geometric parameters of the femurs and tibias obtained from CBCT. The fracture load based on the three-point bending test is also listed.

Parameter	Unit	Femur (N=10)		Tibia (N=10)		P values
		Mean±SD	CV(%)	Mean±SD	CV(%)	
vCtBMD	mg/cm^3	1176.58±73.00	6.20	706.44±62.27	8.81	P<0.0001
CSMI	mm^4	7.97±2.51	31.49	3.56±1.08	30.37	P<0.0001
BSI		9072.00±2971.19	32.75	2645.70±915.36	34.60	P<0.0001
Fracture load	N	109.12±12.51	11.5	91.64±8.60	9.39	0.003

3.2 The correlations between the radiologic measurements and the mechanical test

In the BMD measured using CBCT, the correlations (r) found between the fracture loads and the vCtBMD for the femurs and tibias were 0.63 and 0.78, respectively (Figure 3). For the correlation between the geometric parameters and fracture loads, the correlation (r) between the CSMI (measured using CBCT) and the fracture loads of the femurs and tibias were 0.77 and 0.78, respectively (Figure 4). For the correlation between the parameter (BSI, combined the densitometric parameters and geometric characteristics) and fracture load, the correlations (r) were 0.82 and 0.86 for the femurs and tibias, respectively (Figure 5).

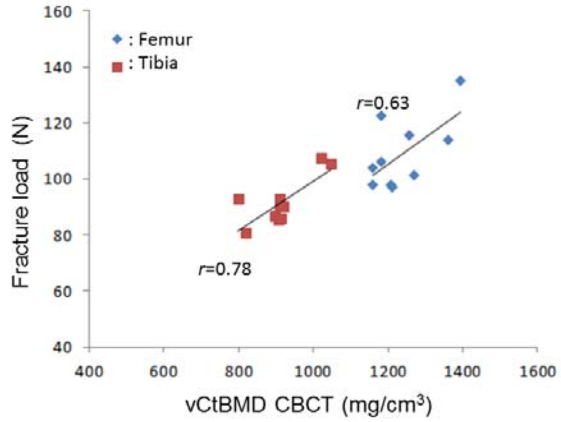

Figure 3. The correlation between fracture load and vCtBMD.

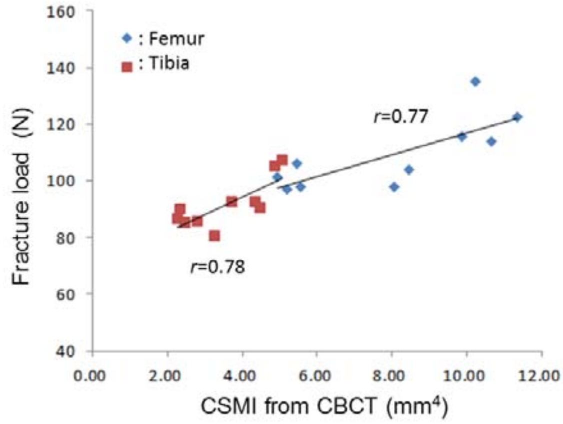

Figure 4. The correlation between fracture load and CSMI.

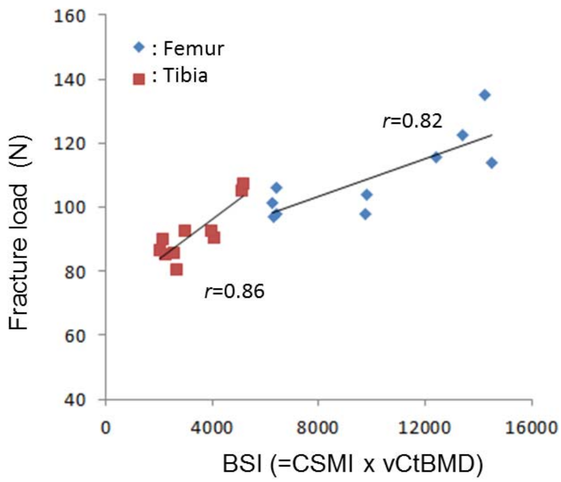

Figure 5. The correlation between fracture load and BSI (BSI=CSMI × vCtBMD).

4. DISCUSSION AND CONCLUSION

Using non-invasive methods to measure BMD for predicting bone strength is an important issue. To this point, DXA has been the most common method. However, DXA only provides two-dimensional information regarding bone density and therefore provides a limited understanding of bone strength behavior. Previous studies have shown that compared to DXA, pQCT provides more information about the geometric parameters of bones, and possesses superior ability for predicting bone strength. Recently, dental CBCT has become a popular method of evaluating alveolar bone density prior to dental implants. Researchers have recognized the ability of CBCT to predict BMD, although no studies have been conducted to predict long bone strength using dental CBCT. This study was the first to evaluate the bone strength of cortical bones using dental CBCT.

Dental CBCT is characterized by low price and small spatial volume as compared to traditional CT and requires low radiological dosages. Because of these advantages, CBCT has become popular in clinical dental diagnosis and treatment services. CBCT can identify and judge the shape of bones precisely because of its ability to differentiate among bone tissues In addition, because it has a higher spatial resolution, it should be capable of measuring the CSMI of rat femurs and tibias accurately, such as those used in this study. In addition to its ability to precisely measure geometric shapes, recent studies have examined the effectiveness of CBCT in identifying bone BMD. Nomura et al. have recently indicated that CBCT might be able to evaluate BMC from the voxel values of dental CBCT.

Our experiment results show that the correlation (*r*) between the obtained BSI (CSMI × vCtBMD) and the femur and tibia fracture loads were 0.82 and 0.86, respectively. These figures were not as high as those obtained by Ferretti et al.[9], where the correlation between the fracture load and the BSI of rat femurs measured using pQCT was 0.94. This may mainly be because Ferretti et al.[9], in addition to using rats that had normal bone quality, used rats that were treated with dexamethasone or aluminum hydroxide, causing a larger variation in the cortical BMD of the specimens. However, in the Siu et al.[10] study, which featured goat femurs and humeri that were of similarly normal bone quality to this study to measure the densitometric and geometric parameters using pQCT, the correlation (*r*) between BSI_{CSMI} and the fracture load of the femurs was only 0.334. Nevertheless, using $BSI_{cross\text{-}sectional\ area(CSA)}$ as an indicator to predict the fracture load of femurs raised the correlation (*r*) to 0.697. In addition, Moisio et al.[11] also used pQCT to measure beagle femurs and found that the adjusted r^2 between the BSI and the fracture load was 0.877. Both the CBCT used in this study and the pQCT used in previous studies to measure the densitometric and geometric combined parameters of bones, such as BSI, yield a better prediction of bone strength than the areal BMD that is measured using DXA. Therefore, results show that, in addition to pQCT, CBCT is an appropriate method for evaluating cortical bone strength (fracture load).

To conclude, ased on the results obtained from *in vitro* rat bones, the vCtBMD, CSMI, and BSI obtained using dental CBCT all provided good predictions of cortical bone bending fracture loads. Furthermore, correlations were found between the BSI (vCtBMD×CSMI) and the fracture loads (*r*=0.82 and 0.86 for femurs and tibias, respectively). Used as a non-invasive method to predict bone strength, dental CBCT, which requires low radiological dosages, can be employed as an alternative to pQCT, especially when frequent radiological examinations must be conducted within a short time period.

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